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AREA-OF-INTEREST DISPLAY RESOLUTION AND STIMULUS CHARACTERISTICS EFFECTS ON VISUAL DETECTION THRESHOLDS

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13. ABSTRACT (Maximum 200 words)

An investigation was conducted to examine the effects of area-of-interest (AOI) display resolution and various stimulus characteristics on visual detection thresholds using the Limited Field-of-View Dome (LFOVD) visual simulation system located at the Aircrew Training Research Division, Human Resources Directorate of the Armstrong Laboratory at Williams Air Force Base, Arizona. Two levels of AOI resolution, which was defined as the width of the line spread function at 50% of the line's maximum luminance, were evaluated. The higher resolution level was 0.081 degree horizontal by 0.071 degree vertical, and the lower resolution level was 0.132 horizontal by 0.121 degrees vertical. The stimuli consisted of computer-generated striped and plain cylinder-shaped objects. The cylinders stood upright on the simulated terrain surface, and the stripes were placed midway between the top and bottom of the cylinders and completely encircled the cylinders. Detection thresholds were determined for both the cylinder stripes and the cylinders. The analysis of the cylinder stripes indicated that the threshold detection distances were greater with the higher resolution AOI and that the detection distances generally increased as stripe size, cylinder height, and cylinder diameter increased. The image generator load management parameters dictated the detection distances for the plain cylinders, except the smallest diameter cylinders.

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PREFACE

The purpose of the present investigation was to examine the effects of area-of-interest (AOI) display resolution and various stimulus variables on visual detection thresholds using the Limited Field-of-View Dome (LFOVD) simulation system located at the Armstrong Laboratory, Aircrew Training Research Division, Williams Air Force Base, Arizona. The research effort was supported by the University of Dayton Research Institute, Contract No. F33615-90-C-0005, in conjunction with Work Unit Nos. 2743-25-17 Flying Training Research Support and 1123-32-01, Visual Display System Functional Requirements.

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> Ms. Susan Wood, who modeled the visual database and served as the primary console operator during data collection,
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> Mr. George Kelly, who derived the line spread functions for the two AOI displays.

AREA-OF-INTEREST DISPLAY RESOLUTION AND STIMULUS CHARACTERISTICS EFFECTS ON VISUAL DETECTION THRESHOLDS

SUMMARY

The present investigation was conducted to assess the effects of area-of-interest (AOI) display resolution and various stimulus characteristics on visual detection thresholds. The Limited Field-of-View Dome (LFOVD) visual simulation system located at the Aircrew Training Research Division of the Armstrong Laboratory, Williams Air Force Base, Arizona, was used in this research. The LFOVD provides two optional AOI sizes: a small, higher-resolution AOI and a large, lower-resolution AOI. The field-of-view (FOV) size of the small AOI was 26.44 degrees horizontal by 20.51 degrees vertical, and the resolution (defined as the width of the line spread function at 50% of the line's maximum luminance) was 0.081 degrees horizontal and 0.071 degrees vertical. The FOV size of the large AOI was 40 degrees horizontal and 30 degrees vertical, and the resolution was 0.132 degrees horizontal and 0.121 degrees vertical. The visual stimuli were striped and plain cylinder-shaped objects; stripe size, cylinder height, and cylinder diameter were varied. Four observers were used, and detection thresholds were collected for both the cylinders and cylinder stripes. The analysis of the thresholds associated with the cylinder stripes indicated that: (1) the detection distances were about 50% greater on the average with the higher resolution AOI than with the lower resolution AOI; (2) the distances were slightly greater for the 8-foot-high cylinder stripes than for the 4-foot-high stripes; (3) the detection distances for the stripes increased as the height of the cylinders increased, and the percentage improvement in detection distance was greater between the shortest and intermediate cylinder heights than between the intermediate and tallest heights used; and (4) the distances increased as the diameter increased, and the percentage improvement in detection distance was greater between the narrowest and intermediate cylinder diameters than between the intermediate and widest

diameters employed. The detection thresholds for most of the plain cylinders were governed by the settings used for the various image generator parameters. Only the smallest diameter cylinders were not influenced by these parameters.

INTRODUCTION

Rationale

Area-of-interest (AOI) displays for flight simulator visual systems were developed in response to a requirement for higher display resolution and image detail (Browder & Chambers, 1988; Chambers, 1982; Fisher & Tong, 1987; Spooner, 1982; Tong & Fisher, 1984). AOI displays consist of a movable, high-resolution inset that is surrounded by a lower resolution, wide-angle peripheral field. The high-resolution inset may be target tracked, eye tracked, head tracked, or simultaneously eye and head tracked. In a target-tracked system, the AOI is displayed at the computed location of the target relative to the observer. Systems equipped with eye-tracking hardware continuously present the AOI in the observer's line of sight, and head-tracked systems position the AOI in the direction the observer's head is pointed. In combined eye- and head-tracked systems, AOI dynamics are governed by the movement of both the observer's eyes and head.

Although image detail is greater in the higher resolution AOI inset than in the surrounding visual field, only a limited area of the visual environment can be displayed in the AOI at any one time. This effect is due to the tradeoff that occurs between AOI resolution and AOI field-of-view (FOV) size. That is, as resolution is increased, there is a corresponding reduction in AOI FOV size. Conversely, AOI resolution diminishes as AOI FOV increases.

Research has shown that observer performance in a flight simulator can be influenced by AOI FOV size as well as resolution. Turner (1984) compared the effects of three AOI conditions on observer performance in a tracking task and a target identification task. The FOV sizes of the AOI examined in the study were 12, 18, and 28 degrees in diameter, and the corresponding resolution levels were 2.0, 3.0, and 4.75 arc minutes (arc min) per line pair. In the tracking task, the observers followed a random turning path that was placed on the floor of a simulated canyon; in the target search task, the observers were required to count the target stimuli placed on the canyon walls as they flew down the canyon. The data indicated that the average of the mean deviations from the path and the number of missed targets were greater for both the smallest (highest resolution) and largest (lowest resolution) AOI sizes when compared with the nominal, 18-degree-diameter AOI.

Statistical analyses of the data revealed that the mean deviations for the 12- and 18-degree AOI sizes were significantly different ($p < 0.05$), and the number of missed targets for the 18- and 28-degree sizes differed significantly. These findings suggest that there is an optimal combination of FOV size and resolution for tasks trained in flight simulators with AOI display systems, such that performance will be adversely affected if the AOI is too small or if the level of resolution is insufficient for the task.

Because observer performance can vary as a function of both AOI FOV size and resolution, the training effectiveness of flight simulators equipped with AOI display systems will be dependent upon the AOI conditions that are used in the simulation. Trainees might employ unrealistic responses to compensate for AOI FOV size or resolution deficiencies, which could have a negative transfer effect in real-world training operations. For this reason, AOI display design guidelines are required to ensure that the AOI conditions that are implemented are consistent with the FOV and resolution requirements of the training tasks.

U.S. Air Force AOI Display Research Program

The Aircrew Training Research Division of the U.S. Air Force Armstrong Laboratory (AL/HRA) at Williams Air Force Base, AZ, has initiated a research program to establish design guidelines for visual simulation systems equipped with AOI displays. The specific purpose of the research program is to determine the AOI FOV and resolution requirements across a range of simulated low-altitude, high-speed military flight tasks. To accomplish this goal, a progressive series of investigations will be conducted in which the effects of various AOI FOV and resolution conditions on observer performance will be evaluated.

The Limited Field-of-View Dome (LFOVD) visual simulation system located at the Armstrong Laboratory will be used in this research program. The LFOVD employs a 24-foot-diameter dome; an F-16A simulator cockpit is enclosed in the dome. A head-tracked AOI display is projected onto the inside surface of the dome, and two different AOI display conditions are available for research purposes. The vertical and horizontal FOV dimensions, resolution, and addressability of the two AOI displays are specified in Table 1. A blend region is included between the AOI inset and the surrounding field to provide a smooth transition between the two areas; the blend regions of the small and large AOI sizes are 2.5 and 5.0 degrees, respectively. The instantaneous FOV, which is specified by the maximum dimensions of the surrounding visual field, is 60 degrees vertical by 140 degrees horizontal. The AOI can be rotated up to 90 degrees left and right, 40 degrees upward, and 22 degrees downward from a point directly in front of the cockpit at eye level.

Table 1. LFOVD AOI Display Characteristics

AOI Size	FOV size (deg) vert	FOV size (deg) horiz	Resolution (deg) vert	Resolution (deg) horiz	Addressability (arc min per pixel) vert	Addressability (arc min per pixel) horiz
Small	21.51	26.44	0.077	0.081	1.41	1.55
Large	30.00	40.00	0.121	0.132	2.31	2.55

Note. Resolution is defined as the width of the line spread function at 50% of the line's maximum luminance, which is a standard measure of resolution (Murch & Virgin, 1985).

A General Electric Advanced Visual Technology System (AVTS) computer image generator with full-color display is used to produce the visual imagery in the dome. Two General Electric light valve projectors present the visual imagery on the dome surface, one for the AOI display and one for the surrounding display. Howard (1989) provides a comprehensive description of the output characteristics of the light-valve projectors. Optical lenses and filters are used to shape the AOI and surrounding field and to produce the blend region. The light valve projectors and the AVTS servo-optical component (SOC), which contains the lenses and blend filter hardware, are located in the dome above the simulator cockpit.

To prevent the occurrence of visual overload from the presence of excessive terrain texturing and an overabundance of objects in the visual scene at any one time, and to prevent objects from abruptly "popping" into the visual scene, the AVTS image generator provides a number of load management parameters that regulate the simulated distance at which the texture and objects are produced in the visual scene. These load management functions include what General Electric terms the Maximum Course Terrain Region, Maximum Fine Terrain Upper Limit, Dynamic Blending, and Flight Visibility Range. The Maximum Course Terrain Region parameter specifies the maximum simulated distance of the course terrain surface, which excludes the terrain texture and the objects on the terrain. The Maximum Fine Terrain Upper Limit function defines the maximum distance of the terrain texture and the objects. Beginning at the distance prescribed by the Maximum Fine Terrain Upper Limit, the terrain and objects gradually transition into the visual scene to prevent popping; the distance encompassed in the transition zone is governed by the Dynamic Blending function. The Flight Visibility Range controls the density of the atmospheric haze.

Purpose and Scope of the Present Investigation

The initial investigation in the series of AOI display evaluations is presented herein. The primary purpose of this investigation was to measure and compare the threshold detection distances associated with the small and large AOI displays used in the LFOVD visual simulation system. This was the first step required in the study series because: (1) information concerning the maximum detection distances is essential to the other studies in the series, and (2) the detection distances corresponding to the two AOI sizes had not been previously quantified.

In this investigation, striped and plain cylinder-shaped objects were presented in the two AOI displays, and detection thresholds were collected for both the cylinder stripes and the plain cylinders. Cylinder height, cylinder diameter, and stripe width were also varied. The influence of the image generator load management parameters on the detection distances of the stimuli was also examined.

METHOD

Observers

Threshold measurements were collected from one female and three male observers ranging in age from 25 to 28 years. Each observer had normal visual acuity, and none wore corrective lenses. Contrast sensitivity was measured for each observer using the Vistech Consultants, Inc., Vision Contrast Test System (VCTS), Model 6500. Test stimuli were monochromatic sinusoidal gratings that varied in contrast. The spatial frequencies of the gratings were 1.5, 3, 6, 12, and 18 cycles per degree. Test results indicated that the four observers had normal contrast sensitivity.

Equipment

The threshold measurements were obtained using the LFOVD visual simulation system. The cockpit instrument lights, the cockpit head-up display (HUD), and the lights in the dome were extinguished during testing, and the only light in the dome was from the display imagery. The head-tracking system was not used in the investigation.

Using hand-held controllers, the observers could increase or decrease the simulated distance of visual stimuli. The distance was displayed digitally in real time on a cathode ray tube (CRT) monitor located on the investigator's work station outside the dome. The observer and investigator communicated via headsets.

Visual Stimuli

The stimuli consisted of striped and plain cylinder-shaped objects placed upright on the terrain surface of the visual database and closed on top to resemble storage tanks in an oil field. Three cylinder heights (i.e., 25, 75, and 100 feet) and three cylinder diameters (i.e., 25, 50, and 75 feet) were combined to form nine cylinder sizes, which are shown in Table 2. Three cylinders were modeled for each cylinder size. One cylinder was

Table 2. Cylinder Sizes

Number	Cylinder height (feet)	Cylinder diameter (feet)
1	50	25
2	50	50
3	50	75
4	75	25
5	75	50
6	75	75
7	100	25
8	100	50
9	100	75

modeled with a 4-foot-high stripe, one with an 8-foot-high stripe, and one without a stripe. The stripe was placed midway between the top and bottom of the cylinder, and the stripe completely encircled the cylinder. The cylinders were light green, and the cylinder stripes were black. The terrain surface was flat, and neither the terrain nor the sky was textured. The terrain was dark tan, and the sky was blue.

A separate cylinder with an 8-foot-high stripe was modeled, which was used for observer practice. The practice cylinder was 100 feet in height and 100 feet in diameter.

The luminance levels in the visual database were matched in the two AOI displays. A Pritchard Spectra Photometer, Model 1980A, was used to measure luminance. The photometer was located at the observer eye point in the dome, and all measurements were taken at a fixed point on the dome surface directly in front of the simulator cockpit. The luminance levels are provided in the appendix.

The luminance levels were calibrated each day of testing to ensure that they were the same for each observer in each test session. The luminance calibration measurements were taken of the 100-foot by 75-foot cylinder, the 8-foot cylinder stripe, the terrain, and the sky; the luminance levels were adjusted, when necessary.

Image Generator Load Management Parameters

The values of the image generator load management parameters used in this investigation were as follows. The Maximum Course Terrain Region, which determined the simulated distance of the far edge of the terrain surface, was set to 80,000 feet. The Maximum Fine Terrain Upper Limit, which defined the maximum simulated distance of the terrain texture and objects, was 80,000 feet. The Dynamic Blending region, which is expressed as the percentage of the Maximum Fine Terrain Upper Limit distance over which the terrain texture and objects transition into the visual scene, was 10%. At this setting, the transition zone for the terrain texture and objects was between 80,000 and 72,000 feet. Finally, the Flight Visibility Range was set to the maximum of 1,600,000 feet. The values used for these parameters were representative of the settings that are commonly used in conjunction with the LFOVD visual simulation system.

Threshold Measurement

Approaching and receding thresholds were collected for both the cylinders and cylinder stripes. The plain and striped cylinders were presented in random order, and one cylinder was presented at a time. The plain cylinders were used to obtain the cylinder detection thresholds, and the striped cylinders were used for the stripe detection thresholds.

To start the threshold measurement sequence, the observer was initialized directly over the cylinder. The observer then operated the hand-held controller to move the aircraft backward in the visual database. The aircraft always moved in a straight line, and the cylinder always appeared directly in front of the observer.

For the striped thresholds, the observer moved the aircraft rearward until the stripe on the cylinder was no longer visible. The observer stopped the rearward movement at this point and verbally signaled the experimenter. After a momentary pause, the experimenter directed the observer to move the aircraft farther rearward, about 3,000 to 5,000 feet, and then reverse direction and move forward until the cylinder was just visible. The observer then paused at this point and signaled. These initial receding and approaching adjustments served as practice, and no data were taken.

Following the practice, the final approaching and receding thresholds were collected; either the approaching threshold was collected first or the receding threshold was collected first. In both cases, the final threshold measurement sequence began at the point where the observer had stopped after the last practice adjustment. The final threshold measurement steps were as follows:

1. Receding Threshold First. When the receding threshold was first, the observer was requested to move toward the cylinder until the stripe was clearly visible, then stop and move slowly rearward until the stripe appeared to vanish. The distance between the cylinder and aircraft at this point was recorded for the receding threshold. After this distance was recorded, the observer was instructed to move farther backward, about 3,000 to 5,000 feet, then reverse direction and approach the cylinder until the stripe was just visible. This distance was recorded as the approaching threshold.

2. Approaching Threshold First. When the approaching threshold was collected first, the observer was instructed to move rearward, about 3,000 to 5,000 feet, then approach the cylinder until the stripe was just discernible. After the distance was recorded, the observer was requested to approach the cylinder until the stripe was very distinct. The observer then moved backward until the stripe was no longer visible, which constituted the receding threshold.

A similar threshold measurement sequence was used for the plain cylinders. For the receding and approaching cylinder thresholds, the observer moved rearward until the entire cylinder disappeared and approached the cylinder until it reappeared.

The observer sat in the cockpit seat during the threshold measurements. The eye-to-dome distance was 12 feet. The seat was elevated to permit the observers to look over the top of the cockpit HUD for an unobstructed view of the cylinders and cylinder stripes. For all threshold measurements, the simulated aircraft altitude was 150 feet above ground level (AGL). The visual scene surrounding the AOI was extinguished during testing, and the AOI was displayed on the dome directly in front of the cockpit.

Procedure

There were four separate test sessions for each observer, two with the small AOI and two with the large AOI. At least 24 hours elapsed between sessions. In each session, all 27 test cylinders, consisting of the 9 plain cylinders and 18 striped cylinders, were presented. Only one AOI size was used in a session, and the order in which the AOI sizes were used across sessions is shown in Table 3. The table also indicates how many receding thresholds were collected first in a session. Since the combined total of plain cylinders and striped cylinders in a session was 27, the number of approaching thresholds that were collected first can be computed by subtracting the number of receding thresholds in each session from 27.

To ensure that the number of approaching thresholds collected first and the number of receding thresholds collected first were equal for each cylinder and cylinder stripe, the following procedure was used. First, 14 of the 27 cylinders were randomly selected. Then, the approaching thresholds were collected first for these 14 plain and striped cylinders in one session with the small AOI and one session with the large AOI for each observer; the receding thresholds were collected first for the same 14 plain and striped cylinders in the other two sessions for each observer.

Table 3. AOI Sizes Used Across Sessions

Observer	Session 1	Session 2	Session 3	Session 4
1	Large (13)	Small (14)	Large (14)	Small (13)
2	Small (14)	Large (13)	Small (13)	Large (14)
3	Large (14)	Small (13)	Small (14)	Large (13)
4	Small (13)	Large (14)	Large (13)	Small (14)

Note. Number in parentheses indicates the frequency the receding thresholds were collected first out of 27.

The purpose of the investigation and the threshold measurement procedure was explained to each of the observers prior to the initial session. The practice cylinder was presented first in each of the sessions, and practice was provided for both the cylinder and cylinder stripe thresholds. The observers were dark adapted for approximately 10 minutes before the sessions were started.

In each session, the observers produced 27 approaching thresholds and 27 receding thresholds, excluding the practice thresholds. Overall, 216 thresholds were recorded for each observer.

RESULTS

Cylinder Stripe Thresholds

The detection thresholds associated with the cylinder stripes are presented in Figures 1 and 2. Figure 1 shows the threshold distances of the 4-foot stripes for the two levels of AOI resolution and nine cylinder sizes. The threshold distances of the 8-foot stripes are shown in Figure 2. Each bar in the figures represents the mean of the approaching and receding thresholds from two sessions for the four observers.

A four-factor analysis of variance (ANOVA) with repeated measures was used to analyze the cylinder stripe threshold data. The factors were AOI resolution, cylinder height, cylinder diameter, and cylinder stripe size.

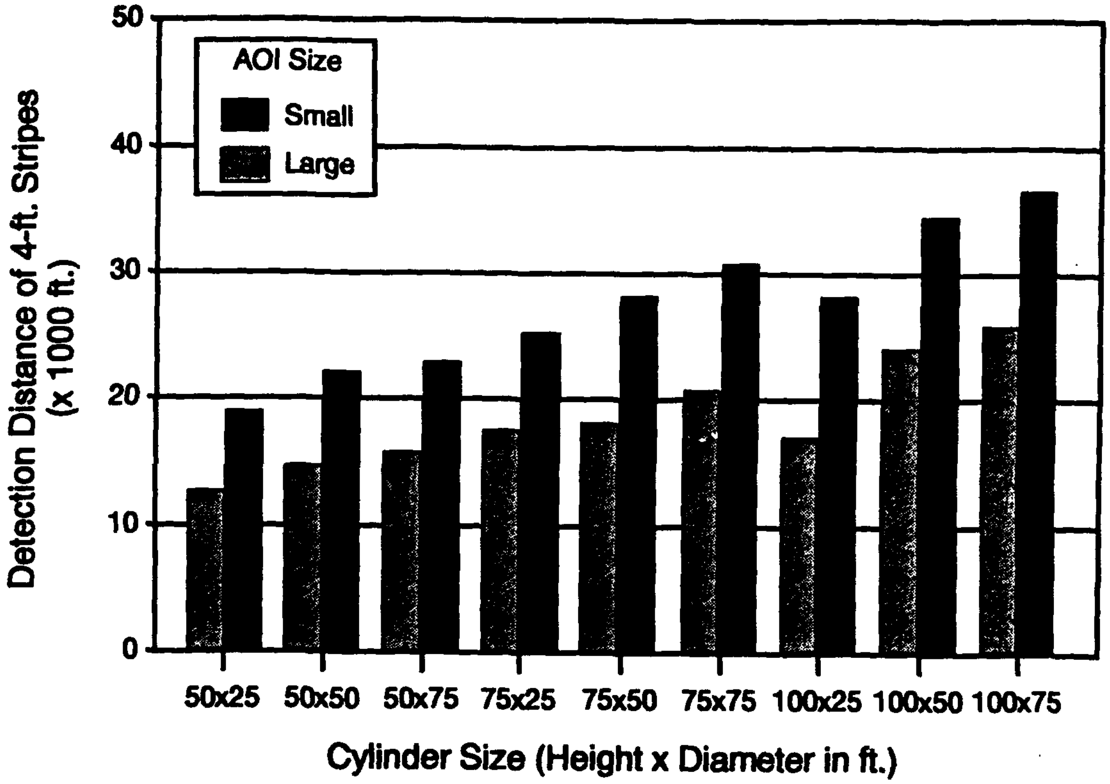

Figure 1. Detection distance of 4-foot stripes as a function of AOI size and cylinder size.

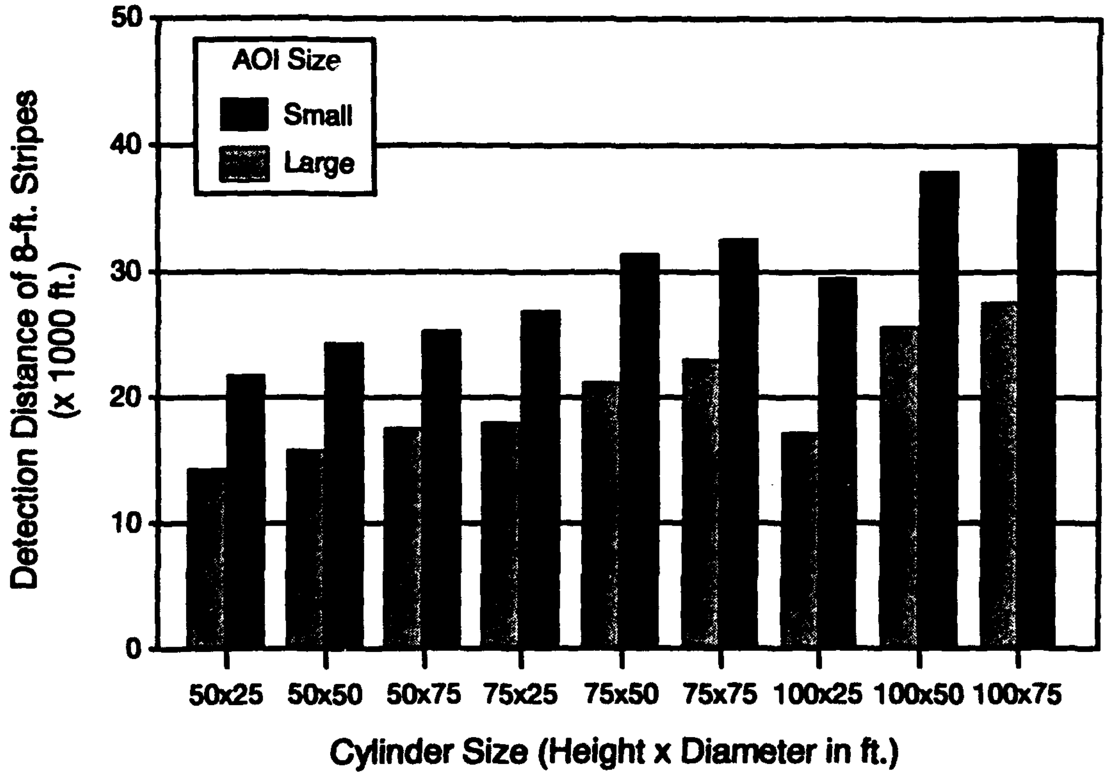

Figure 2. Detection distance of 8-foot stripes as a function of AOI size and cylinder size.

The analysis indicated that the cylinder stripe thresholds for the two levels of AOI resolution were significantly different, $F(1,125) = 2887.36$, $p < 0.01$. The mean threshold distance was 28,830 feet for the small (higher resolution) AOI and 19,230 feet for the large (lower resolution) AOI. The analysis also showed that the threshold distances varied as a function of cylinder stripe size, $F(1,125) = 113.75$, $p < 0.01$. The mean threshold distance was 23,077 feet for the 4-foot stripe and 24,983 feet for the 8-foot stripe. The threshold distances were also significantly related to both cylinder height, $F(2,125) = 1055.32$, $p < 0.01$, and cylinder diameter, $F(2,125) = 388.16$, $p < 0.01$. The mean cylinder stripe threshold distances of the three cylinder heights were 18,781 feet for the 50-foot-high cylinder, 24,510 feet for the 75-foot cylinder, and 28,799 feet for the 100-foot cylinder. The mean cylinder-stripe thresholds of the 25-foot-, 50-foot-, and 75-foot-diameter cylinders were 20,637 feet, 24,916 feet, and 26,537 feet, respectively. Least-significant difference (LSD) tests indicated that each of the pair-wise comparisons of the mean thresholds for cylinder height and cylinder diameter was significant, $p < 0.05$.

Four two-way interactions were statistically significant: (1) AOI resolution by cylinder height, $F(2,125) = 56.58$, $p < 0.01$, (2) AOI resolution by stripe size, $F(1,125) = 5.76$, $p < 0.05$, (3) cylinder height by cylinder diameter, $F(4,125) = 47.37$, $p < 0.01$, and (4) cylinder diameter by stripe size, $F(2,125) = 3.88$, $p < 0.05$. The distribution of the mean threshold distances for these interactions are provided in Figures 3 through 6. LSD tests of the mean thresholds indicated that each pair-wise comparison was significant, $p < 0.05$, for all four interactions.

Cylinder Thresholds

The detection thresholds corresponding to the nine plain cylinders with the small and large AOI sizes are provided in Figure 7. Each bar in the figure represents the mean of the approaching and receding thresholds for two sessions across the four observers.

Figure 7 illustrates the mean detection thresholds relative to the settings of two image generator load management parameters, the Maximum Fine Upper Terrain Limit and Dynamic Blending. Inspection of the means reveals that the detection distances for all but the 25-foot-diameter cylinders with the large AOI fell within the dynamic blending region. Figure 7 also indicates that the detection thresholds for the cylinders that were within the dynamic blending region varied somewhat as a function of AOI size as well as cylinder size. To test whether these thresholds were significantly different, two separate statistical analyses were conducted. The first analyzed the detection thresholds for the 50- and 75-foot-diameter cylinders with both the small and large AOI sizes; the second analyzed the detection thresholds for each of the cylinder sizes with the small AOI. Two analyses were required

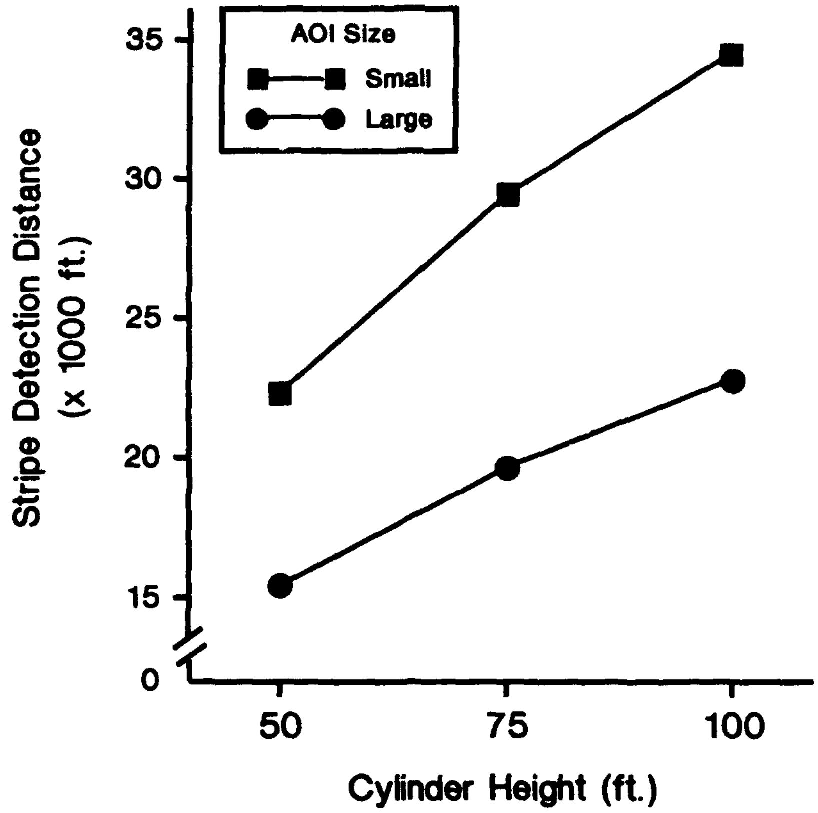

Figure 3. Stripe detection distance as a function of AOI size and cylinder height.

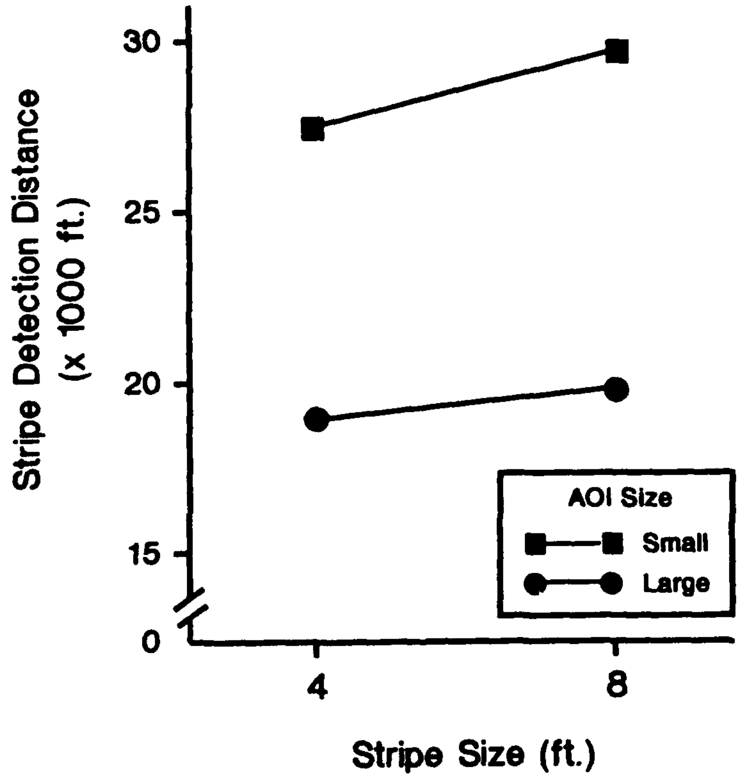

Figure 4. Stripe detection distance as a function of AOI size and stripe size.

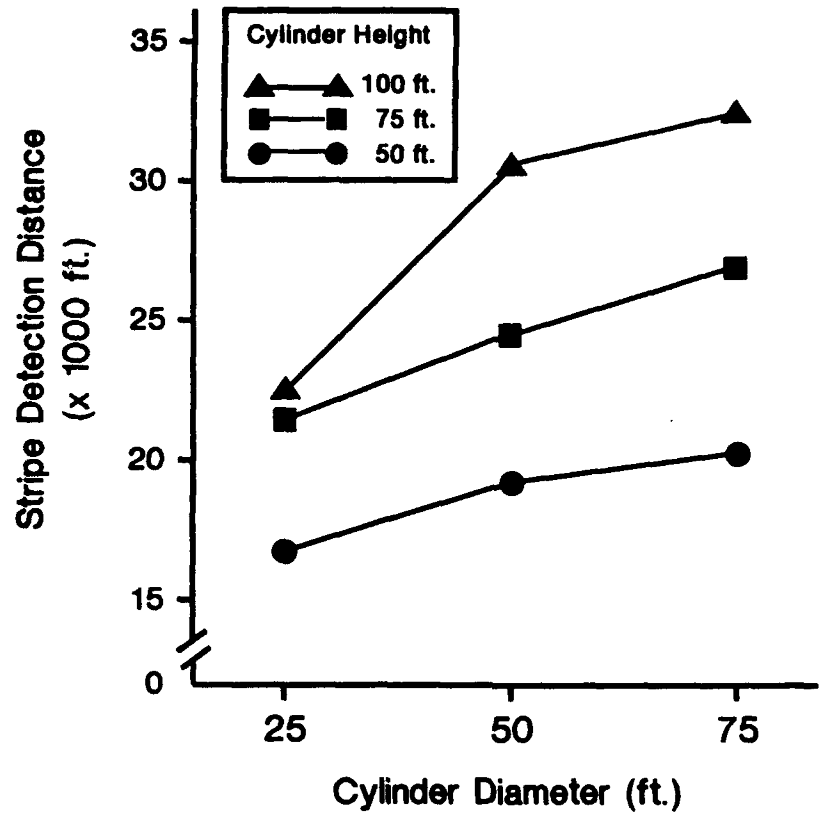

__Figure 5__. Stripe detection distance as a function of cylinder height and cylinder diameter.

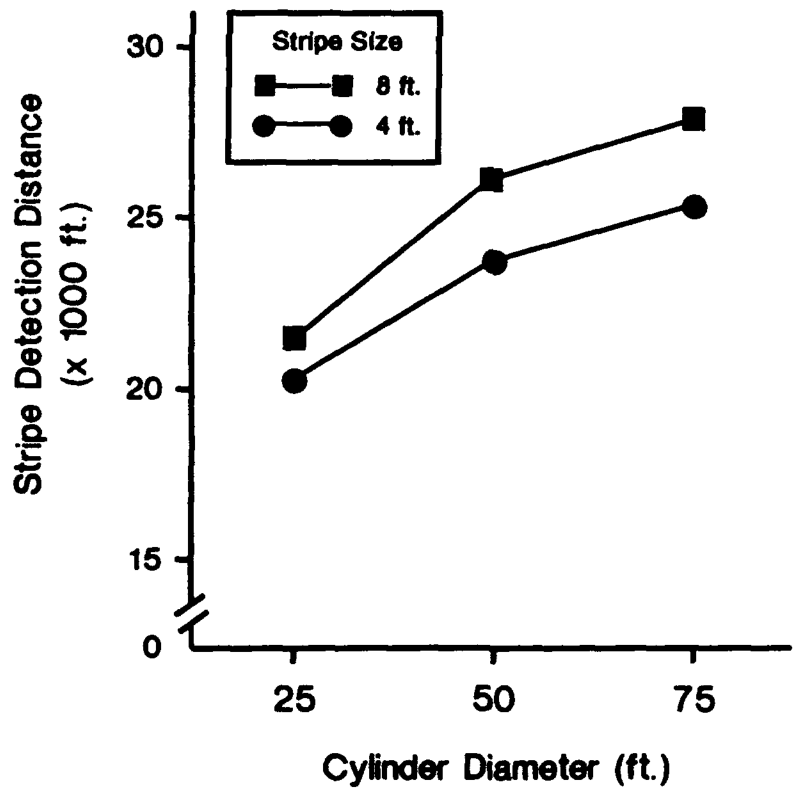

__Figure 6__. Stripe detection distance as a function of stripe size and cylinder diameter.

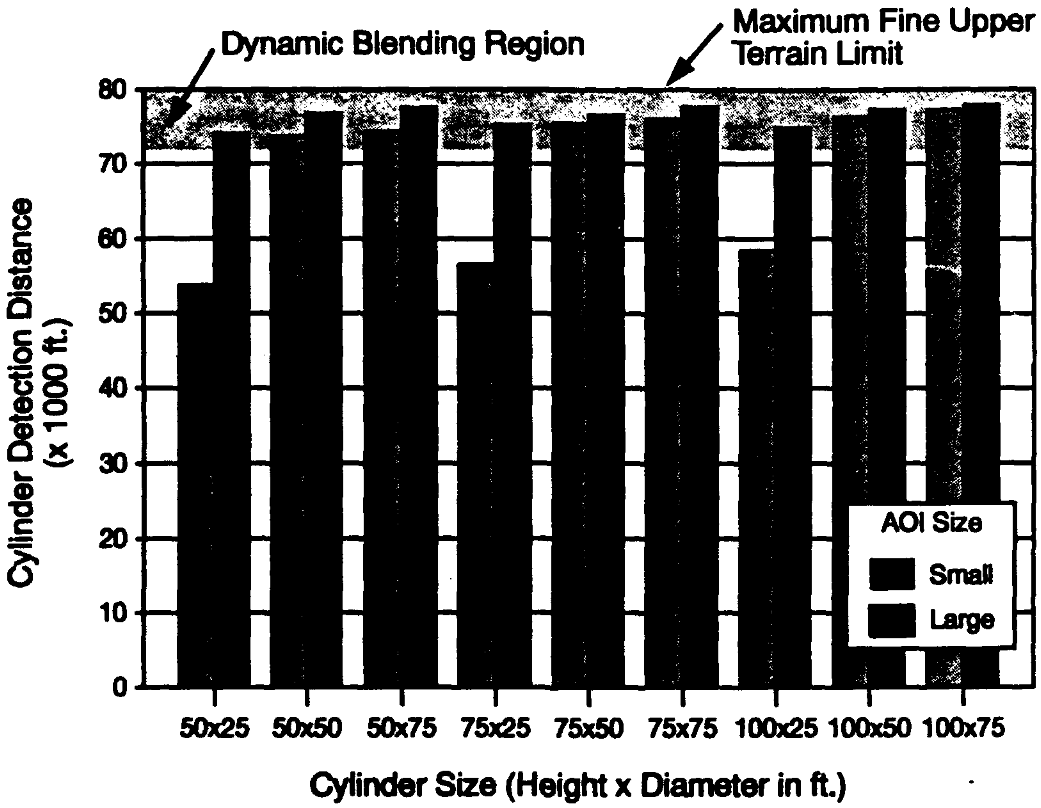

Figure 7. Cylinder detection distance as a function of AOI resolution and cylinder size.

because the thresholds for the 25-foot-diameter cylinders with the large AOI were excluded, which resulted in unequal data sets for the small and large AOI sizes.

A three-factor ANOVA with repeated measures was used in the first analysis. The factors were AOI size (small and large), cylinder height (50, 75, and 100 feet), and cylinder diameter (50 and 75 feet). Significant main effects were obtained for: (1) AOI size, $F(1,38) = 134.88$, $p < 0.01$; (2) cylinder height, $F(2,38) = 32.67$, $p < 0.01$; and (3) cylinder diameter, $F(1,38) = 25.16$, $p < 0.01$. The mean threshold distances associated with the small and large AOI sizes were 77,447 and 75,568 feet, respectively. The mean threshold distances for the 50-, 75-, and 100-foot-high cylinders were 75,698, 76,526, and 77,299 feet; the thresholds were 76,102 and 76,913 feet for the 50- and 75-foot-diameter cylinders. The LSD tests of the main effect of cylinder height were significant ($p < 0.05$) for all pair-wise comparisons.

There was also a statistically significant two-way interaction between AOI size and cylinder height, $F(2,38) = 18.81$, $p < 0.01$; the mean threshold detection distances obtained with the small and large AOI sizes are plotted as a function of cylinder height in

Figure 8. In the subsequent pair-wise comparison of the mean thresholds in the figure, the only LSD tests that were not significant ($p > 0.05$) were between the three cylinder heights within the small AOI. None of the other interactions was statistically significant.

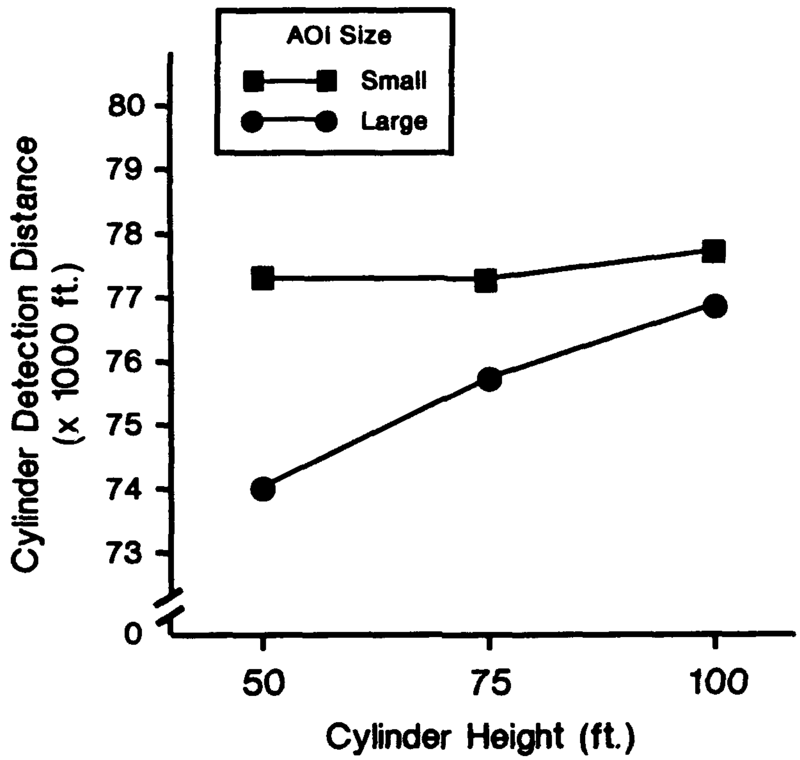

Figure 8. Cylinder detection distance as a function of AOI size and cylinder height.

Next, the threshold data obtained with the small AOI were analyzed. A two-factor ANOVA with repeated measures was used for this analysis. The factors were cylinder height and cylinder diameter. The cylinder height main effect was significant, $F(2,24) = 7.07$, $p < 0.01$, as was the cylinder diameter main effect, $F(2,24) = 215.66$, $p < 0.01$ and the cylinder height by cylinder diameter interaction, $F(4.24) = 4.33$, $p < 0.01$. The mean threshold distances associated with the main effect of cylinder height were 76,272 feet, 76,653 feet, and 76,823 feet for the 50-foot, 75-foot, and 100-foot cylinder heights, respectively, and the means of the main effect of cylinder diameter were 74,854 feet, 77,009 feet, and 77,884 feet for the 25-foot, 50-foot, and 75-foot cylinder diameters. The mean distances for the two-way interaction are provided in Figure 9. LSD tests of the main effects revealed that all pair-wise mean comparisons were significant ($p < 0.05$) except between the 50-foot and 75-foot cylinder heights. For the interaction, only five mean comparisons were not significant ($p > 0.05$). The respective heights and diameters of the cylinders corresponding to these five comparisons were: (a) 50 x 50 and 75 x

50, (b) 50 x 75 and 75 x 75, (c) 50 x 75 and 100 x 75, (d) 75 x 25 and 100 x 25, and (e) 75 x 75 and 100 x 75.

A final statistical analysis was conducted to compare the effects of cylinder height on the detection thresholds for the three 25-foot-diameter cylinders with the large AOI. A single-factor ANOVA with repeated measures was used in the analysis, which indicated that the thresholds were not significantly different ($p > 0.05$). The mean threshold distances for the 50-, 75-, and 100-foot cylinder heights were 53,789, 56,682, and 58,475 feet, respectively.

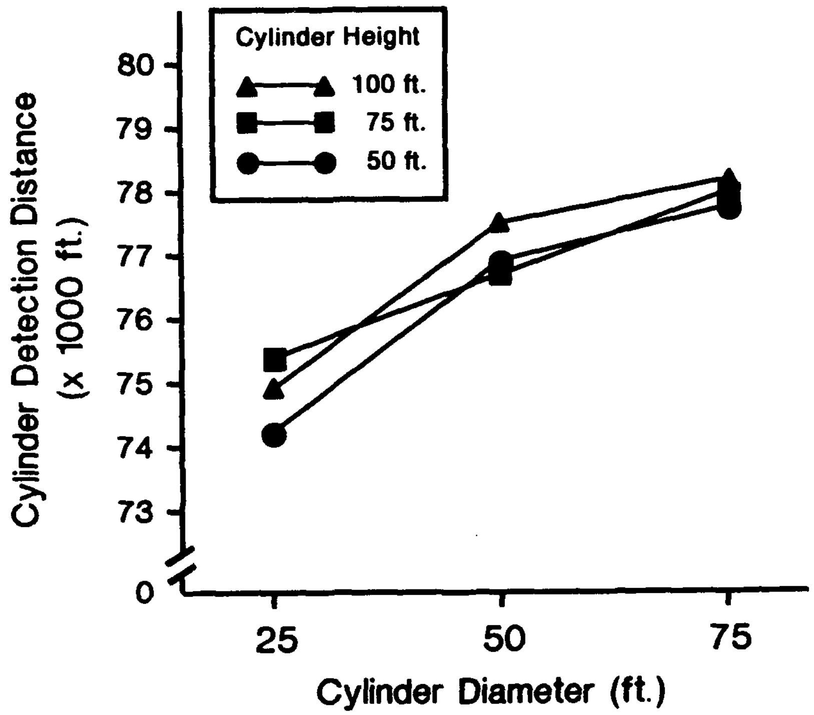

Figure 9. Cylinder detection distance as a function of cylinder height and cylinder diameter.

DISCUSSION

Cylinder Stripe Detection Thresholds

The analysis indicated that the detection thresholds for the cylinder stripes varied as a function of AOI size (resolution). In addition to the statistically significant main effect of AOI size, two significant two-way interactions involving AOI size were obtained, one with cylinder height (Figure 3) and one with stripe size (Fig. 4). In both of these interactions, the percentage improvement in stripe detection distance provided by the higher resolution AOI display was relatively constant across the various cylinder heights and stripe sizes. The percentage differences in the stripe detection distances between the two AOI sizes corresponding to the 50-, 75-, and 100-foot-high cylinders in Figure 3 were 49.27%, 46.95%, and 52.94%, respectively, and the percentage differences between the large and small AOI sizes in Figure 4 were 49.59% and 50.23% for the 4- and 8-foot cylinder stripes, respectively. As a result of the constant percentage improvement, the magnitude of the difference in the mean stripe detection thresholds between the small and large AOI sizes increased as the height of the cylinders increased, and the magnitude of the threshold differences between the two AOI sizes increased as stripe size increased. It is hypothesized that the slight variability in the percentage differences between the threshold distances across the cylinder heights and stripe sizes were attributable to random variations in the observers' simulated distance adjustments. It will be recalled that the observers themselves adjusted the simulated stripe distances, which would have produced a certain degree of variability in the threshold distances.

In the detection task used in the present investigation, the observers merely had to determine when the stripes were present (approaching thresholds) or were no longer visible (receding thresholds). Other research has shown that display resolution has a similar effect on target orientation recognition threshold distances. Kennedy, Berbaum, Collyer, May, and Dunlap (1988) evaluated the effects of resolution and other display characteristics on the simulated distances from which observers could identify the orientation of aircraft imagery in a flight simulator. The images were computer generated, and the observers' task was to indicate whether the aircraft were climbing or diving. Four levels of display resolution were compared: 1.0, 1.3, 1.6, and 1.9 arc min per line pair. The analysis showed that the target orientation recognition thresholds varied significantly between the four resolution conditions. It was reported that the threshold recognition distances increased as resolution increased and that the threshold distances were 20 percent greater with the highest resolution condition than the thresholds with the lowest threshold tested.

The analysis of the stripe detection thresholds also showed that the main effect of stripe size was statistically significant and that stripe size interacted with AOI size, as described above, and with cylinder diameter. In the AOI size by stripe size interaction, which is presented in Figure 4, the mean threshold distance of the 8-foot stripe was 8.44% greater than the mean threshold distance of the 4-foot stripe using the small AOI size and 7.98% with the large AOI. In the stripe size by cylinder diameter interaction, the difference in detection thresholds between the 4- and 8-foot stripe sizes increased as the diameter of the cylinders increased, which is shown in Figure 6. The percentage differences between the mean detection distances of the 4- and 8-foot stripes were 6.00%, 9.33%, and 9.03%, respectively, for the 25-, 50-, and 75-foot-diameter cylinders. It is postulated that the variability in these percentage differences was due in large measure to random variations in stripe distance adjustment promulgated by the observers.

The stripe detection thresholds were also influenced by the height of the cylinders. In the analysis, the main effect of cylinder height was statistically significant, as were the AOI size by cylinder height interaction and the cylinder height by cylinder diameter interaction. In the AOI size by cylinder height interaction (Fig. 3), the stripe detection distances increased as cylinder height increased; and with both AOI sizes, the percentage increases in the mean threshold distances were greater between the 50- and 75-foot-high cylinders than between the 75- and 100-foot-high cylinders. The percentage differences in the mean stripe thresholds between the 50- and 75-foot-high and between the 75- and 100-foot-high cylinders were 30.68% and 19.39% for the small AOI, and the corresponding differences for the large AOI were 31.73% and 14.72%. The percentage differences in the mean threshold distances between the 50-and 75-foot-high cylinders were nearly the same (i.e., 27.69%, 29.64%, and 33.74%, respectively) across the various cylinder diameters in the cylinder height by cylinder diameter interaction (Figure 5). The percentage differences were virtually identical (i.e., 23.11% and 21.79%, respectively) between the 75- and 100-foot-high cylinders that had 50- and 75-foot diameters. The difference in the mean detection distances, however, between the 75- and 100-foot-high cylinders was only 9.45% when the cylinder diameter was 25 feet, which could account for the significant cylinder height by cylinder diameter interaction.

It can be concluded from this analysis that: (1) the discriminability of the stripes improved when the height of the cylinders was increased, (2) the percentage improvement in the stripe detection thresholds was greater when the cylinder heights there were increased from 50 to 75 feet than when the cylinders were increased from 75 to 100 feet, and (3) the percentage improvement in stripe visibility produced by increasing the cylinder height was simultaneously dependent on the diameter of the cylinders and resolution of the AOI display. It should be noted, however, that there were two instances in which there was a small decline in the mean stripe detection thresholds when the cylinder height was increased. These results are most likely due to random distance adjustment variations by the observers. It can be seen in Figures 1 and 2 that the mean distances associated with the 100-foot-high by 25-foot-diameter cylinder were slightly less than the mean distances associated with the 75-foot-high by 25-foot-diameter cylinder for both the 4- and 8-foot-high stripe sizes under the large AOI size condition. This variance suggests that the stripe thresholds corresponding to the 25-foot-diameter cylinders in the large AOI become asymptote when the cylinder height reaches 75 feet.

The analysis also indicated that the cylinder diameter influenced the thresholds for the cylinder stripes. When the cylinder diameter was increased, both the total area of the cylinder and the width of the cylinder stripe were simultaneously increased. Therefore, when reference is made to cylinder diameter, it also implies a concomitant increase in stripe width. In the analysis, the main effect of cylinder diameter was statistically significant, as were the cylinder height by cylinder diameter interaction and the stripe size by cylinder diameter interaction.

It is evident in Figure 5, which depicts the cylinder height by cylinder diameter interaction, that there was a progressive increase in the thresholds of the cylinder stripes as cylinder diameter was increased for each of the cylinder heights. In addition, for each of the three cylinder heights, the percentage improvement in the stripe detection distance was substantially greater when the cylinder diameter was increased from 25 to 50 feet than when the diameter was increased from 50 to 75 feet. When the cylinder diameter was increased from 25 to 50 feet, the percentage increases in the stripe threshold distance were 12.53%, 14.25%, and 32.93%, respectively, for the three cylinder heights in ascending order. When the cylinder diameter was increased from 50 to 75 feet, the percentage increases were 4.53%, 7.82%, and 6.67%, respectively, for the corresponding cylinder heights. The same trends also occurred for the 4- and 8-foot stripe sizes in the stripe size by cylinder diameter interaction, which is presented in Figure 6. The percentage increases for the 4- and 8-foot-high stripe sizes were 18.81% and 22.55%, respectively, when the cylinder diameter was increased from 25 to 50 feet, and 6.66% and 6.36% when the diameter was increased from 50 to 75 feet.

Based on these interactions, the following conclusions can be drawn with respect to cylinder diameter: (1) the discriminability of the stripes increased as the width of the stripes and the area of the cylinders increased, (2) the percentage improvement in the stripe thresholds was greater when the cylinder diameter was increased from 25 to 50 feet than when the diameter was increased from 50 to 75 feet, and (3) the percentage improvement in stripe detection distance associated with the increase in cylinder diameter simultaneously varied as a function of cylinder height and stripe height.

It should be mentioned in closing that when the various dimensions of one of the striped cylinders were doubled, the mean stripe detection distance was essentially doubled. In the present investigation, the dimensions of the 100-foot-high by 50-foot-diameter cylinder with the 8-foot-high stripe were exactly twice the dimensions of the 50-foot-high by 25-foot-diameter cylinder with the 4-foot stripe. It was observed that the mean stripe threshold distance was, for all practical purposes, twice as great for the larger striped cylinder for both AOI sizes, which can be seen by comparing Figures 1 and 2.

Cylinder Detection Thresholds

In the present investigation, the image generator load management parameters were set such that the terrain texture and the cylinders would completely blend into the visual scene over a simulated range of 72,000 to 80,000 feet. This setting would influence only those cylinders that would normally be visible within that range. These load management parameter settings were selected because they were representative of the settings that are typically used in flight simulator operations with this image generator to prevent a system overload from an excessive amount of texturing and an overabundance of objects in the scene at one time.

Figure 7 shows that, except for the 25-foot-diameter cylinders in the large AOI, the mean detection thresholds for the plain cylinders were within the dynamic blending region. The two analyses associated with these latter thresholds indicated that the cylinder threshold distances varied significantly as a function of AOI size, cylinder height, and cylinder diameter. The range, however, between the minimum and the maximum threshold distances within the dynamic blending area was only a little over 4,000 feet. The minimum detection threshold was 73,772 feet, which was associated with the 50-foot-high by 50-foot-diameter cylinder in the large AOI, and the maximum threshold was 78,049 feet, which corresponded to the 100-foot-high by 75-foot-diameter cylinder.

The 25-foot-diameter cylinders in the large AOI were the only plain cylinders that were not influenced by the settings of the image generator load management parameters. Therefore, the detection thresholds for these cylinders represent the maximum possible simulated distances from which the cylinders could be seen by the observers. Based on the findings by Thomas (1978) that the visibility of rectangular objects increases as the longer dimension (length) is increased, it was anticipated in the current research that the detection thresholds of the 25-foot-diameter cylinders would increase as the height of the cylinders increased. It was observed that the mean thresholds increased as the height of the cylinders was increased, but the analysis showed that the threshold differences between the 50-, 75-, and 100-foot-high cylinders were not statistically significant.

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APPENDIX: STIMULI LUMINANCE AND CONTRAST LEVELS

The luminance levels of the visual imagery in both the small and large AOI were measured. The luminances of the striped cylinders and the cylinder stripes in the small AOI are shown in Table A-1, along with the luminance contrast levels. In Table A-2, the luminance and contrast levels in the large AOI are presented, and Table A-3 provides the luminance levels of the plain cylinders and terrain, as well as the corresponding contrast percentages in both AOI displays. The sky luminance was 0.29 foot-lambert in both the small and large AOI displays, and the sky/ground contrast was 50.85%.

A Pritchard Spectra Photometer, Model 1980A, was used for the luminance measurements. The photometer was located at the observer eye point in the dome, and all measurements were taken at the same point on the dome surface directly in front of the simulator cockpit. The striped-cylinder luminance readings (Tables A-1 and A-2) were taken midway between the stripe and the bottom of the cylinder and midway between the left and right sides of the cylinders. The luminance levels were measured at the same position on the plain cylinders (Table A-3) as on the striped cylinders, and the stripe luminances (Tables A-1 and A-2) were measured halfway between the top and bottom and the left and right ends of the stripe. The simulated slant range from the center of gravity (CG) of the aircraft to the center of the bottom half of the cylinders was 559 feet, and the slant range from the CG to the cylinder stripes was 558 feet.

The contrast values in the tables were determined by the equation:

$$\text{Contrast (\%)} = 100 \times \frac{L_{max} - L_{min}}{L_{max}}$$

where Lmax is the luminance of the brighter area and Lmin is the luminance of the darker area.

Table A-1. Cylinder and Stripe Luminance and Contrast Levels in Small AOI

Cylinder size (h x d)	4-foot Stripe Cylinder lum (fL)	4-foot Stripe Stripe lum (fL)	4-foot Stripe Contrast (%)	8-foot Stripe Cylinder lum (fL)	8-foot Stripe Stripe lum (fL)	8-foot Stripe Contrast (%)
50x25	1.36	0.15	88.97	1.36	0.12	91.18
50x50	1.39	0.16	88.49	1.39	0.13	90.65
50x75	1.39	0.16	88.49	1.39	0.14	89.93
75x25	1.37	0.15	89.05	1.37	0.13	90.51
75x50	1.40	0.16	88.57	1.40	0.14	90.00
75x75	1.41	0.17	87.94	1.40	0.14	90.00
100x25	1.38	0.15	89.13	1.37	0.13	90.51
100x50	1.40	0.16	88.57	1.40	0.14	90.00
100x75	1.40	0.17	87.86	1.40	0.14	90.00

Table A-2. Cylinder and Stripe Luminance and Contrast Levels in Large AOI

Cylinder size (h x d)	4-foot Stripe Cylinder lum (fL)	4-foot Stripe Stripe lum (fL)	4-foot Stripe Contrast (%)	8-foot Stripe Cylinder lum (fL)	8-foot Stripe Stripe lum (fL)	8-foot Stripe Contrast (%)
50x25	1.35	0.15	88.89	1.35	0.12	91.11
50x50	1.36	0.15	88.97	1.36	0.13	90.44
50x75	1.38	0.16	88.41	1.38	0.14	89.86
75x25	1.36	0.15	88.97	1.36	0.13	90.44
75x50	1.38	0.16	88.41	1.38	0.14	89.86
75x75	1.39	0.16	88.49	1.39	0.14	89.93
100x25	1.36	0.15	88.97	1.36	0.14	89.71
100x50	1.39	0.16	88.49	1.39	0.14	89.93
100x75	1.40	0.17	87.86	1.40	0.14	90.00

Table A-3. Cylinder and Terrain Luminance and Contrast Levels

Cylinder size (h x d)	Small AOI Cylinder lum (fL)	Small AOI Terrain lum (fL)	Small AOI Contrast (%)	Large AOI Cylinder lum (fL)	Large AOI Terrain lum (fL)	Large AOI Contrast (%)
50x25	1.36	0.16	88.24	1.36	0.16	88.24
50x50	1.39	0.16	88.49	1.36	0.16	88.24
50x75	1.40	0.16	88.57	1.38	0.16	88.41
75x25	1.38	0.16	88.41	1.36	0.16	88.24
75x50	1.40	0.16	88.57	1.38	0.16	88.41
75x75	1.41	0.16	88.65	1.39	0.16	88.49
100x25	1.38	0.16	88.41	1.36	0.16	88.24
100x50	1.40	0.16	88.57	1.39	0.16	88.49
100x75	1.40	0.16	88.57	1.40	0.16	88.57